EFFECTS OF HOT-WIRE MEASUREMENT IN WALL-BOUNDED FLOWS STUDIED VIA DIRECT NUMERICAL SIMULATION

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Abstract The effect of limited spatial and temporal resolution for hot-wire anemometry is investigated using recent DNSes of a zero-pressure-gradient turbulent boundary layer in the range of Re_θ=4000-6500, and channels at comparable Re_τ. Different spanwise filters are applied to the different velocity components to reproduce the effect of finite wire lengths. Results show that the streamwise turbulent energy at the buffer layer is severely attenuated, while the logarithmic and outer regions are less sensitive to the length of the wire. Attenuation of the streamwise energy seems to be Reynolds independent for the present range of Reynolds numbers, and spectral results are used to predict what the behavior will be beyond that range.

INTRODUCTION

Wall-bounded turbulent flows such as boundary layers, channels, pipes, etc. are subjects of intensive research because of their technological importance. In the past few decades important milestones have been achieved in understanding those flows, in part due to the improvement of the measurement techniques, and to the direct numerical simulations made possible by the continued computational growth. This has lead to high-quality experimental and numerical experiments at high and relatively-high Reynolds numbers respectively. In experiments, hot-wire anemometry (HWA) is a popular experimental technique to measure statistics in turbulent flows. However, special precautions must be taken to prevent filtering of the energy-containing eddies, either spatially due to the finite length of the wire (l_w) or temporally, due to instrumentation response (or equivalently, to the spatial averaging of inclined wires). The former effect was first reported in the late thirties [3], and further extended in [5, 6, 1, 4] among others. In the present study we mimic the effect of the spatial and temporal filtering on the three velocity intensities using a recent DNS database of a turbulent boundary layer at moderately-high Reynolds numbers.

METHODS

A DNS of a turbulent boundary layer is conducted in a parallelepiped over a flat plate with periodic boundary conditions span-wise, and non-periodic in streamwise direction. The velocity components in the streamwise (x), wall-normal (y), and span-wise (z) directions are u, v and w, respectively. The + superscript denotes quantities normalized with the x-dependent friction velocity u_τ and kinematic viscosity ν. The main parameters of the simulation are listed in table 1.

Case	Re_θ	$(L_x, L_y, L_z)/\theta$	$\Delta x^+, \Delta y^+, \Delta z^+$	N_x, N_y, N_z	Tu_τ/δ
TBL	2780-6650	$547 \times 29 \times 84$	$7.00 \times 0.32 \times 4.07$	$15361 \times 535 \times 4096$	6

Table 1: Parameters for the turbulent boundary layer. L_x, L_y and L_z are the box dimensions along the three axes. N_x, N_y and N_z are the collocation grid sizes. The momentum thickness θ, the 99% of the boundary layer thickness δ, and the friction velocity u_τ are taken at the middle of the box. T is the total time over which statistics have been compiled.

The filtered streamwise velocity $u_{fil}(x, y, z; l_w)$ measured by a single hot wire and its Fourier transform can be approximated by [6],

$$u_{fil}(x,y,z;l_w) = \frac{1}{l_w}\int_{-l_w/2}^{l_w/2} u(x,y,z)dz \qquad \hat{u}_{fil}(x,y,k_z;l_w) = \frac{\sin(k_z l_w/2)}{k_z l_w/2}\hat{u}(x,y,k_z) \tag{1}$$

in which k_z is the span-wise wavenumber. Thus, the attenuation due to the length of the wire can be approximately reproduced by filtering the original DNS signal with a span-wise boxcar filter, although the filter length should be slightly shorter than the actual sensor, since the real temperature distribution along the wire is not constant [2]. Time sampling only results in attenuation of the intensities if the signal is explicitly filtered to avoid aliasing of the spectrum.

RESULTS

The streamwise turbulence intensity (denoted by u'^{2+}) has been calculated from the filtered DNS turbulent boundary layer data for all the wall-normal locations and for different wire lengths, in the range l_w^+=1-300. Different Reynolds numbers are considered, for which u'^{2+} is compiled over the span-wise and a fraction $(\pm\delta)$ of the streamwise direction. Figure 1(a)

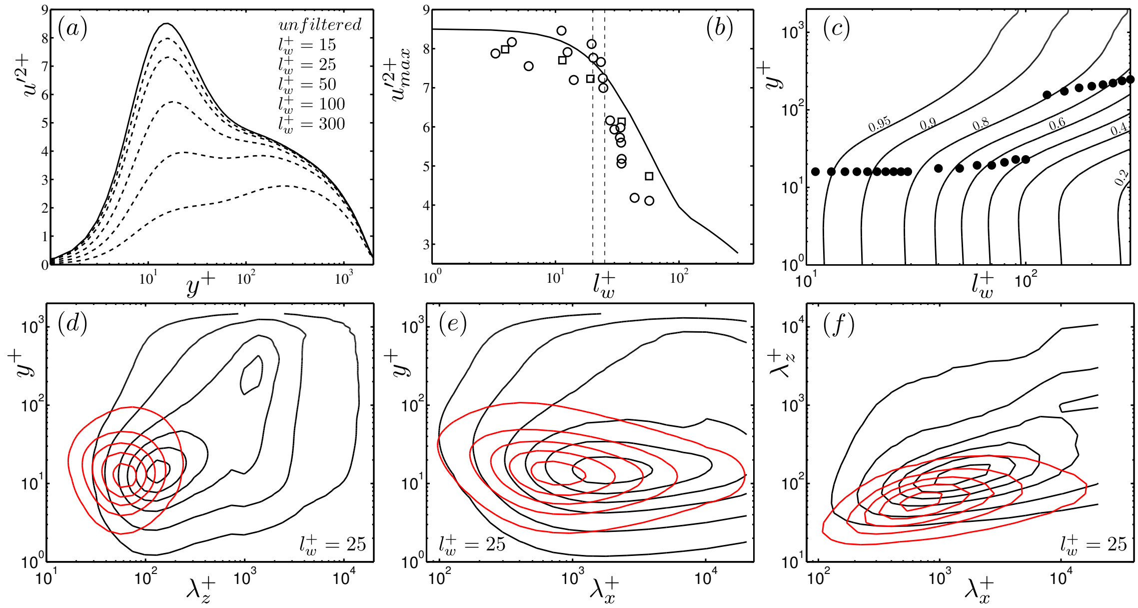

Figure 1: Attenuation of u'^{2+} due to spatial spanwise filtering. (a) Boundary layer u'^{2+} profile at $Re_\theta = 6500$. Unfiltered ━ and filtered profiles – – – for different wire lengths l_w^+. (b) Maximum u'^{2+} as a function of l_w^+. Boundary layer (DNS) at $Re_\theta = 6500$, ━; channel (DNS) [2] $Re_\tau = 934$, □; experimental boundary layer [5] at $Re_\theta = 2620$, ○. (c) Contours of signal attenuation $u'^{2+}_{fil}/u'^{2+}_{unf}$ as a function of the distance to the wall y^+ and l_w^+ for the boundary layer (DNS) at $Re_\theta = 6500$. Symbol • stands for the wall-normal position in which the maximum value is attained for each l_w^+. One-dimensional premultiplied energy and missing energy spectrum $k_z\phi_{uu}^+$ (c) and pseudo-spectrum $k_x\phi_{uu}^+$ (d) with y^+ at $Re_\theta = 4500$ for $l_w^+ = 25$. Black lines: 2% and 0.1:0.2:0.9 contours of the maximum of the spectrum. Red lines: 0.1:0.2:0.9 contours of the maximum of the missing energy spectrum. (f) Two-dimensional premultiplied pseudo-spectrum $k_z k_x \phi_{uu}^+$ for $l_w^+ = 25$ at $y^+ \approx 15$, where u'^{2+} peaks.

displays the effect of several l_w^+ on the profile of u'^{2+} at Re_θ=6500, showing that for even a relatively small probe $l_w^+ \approx 25$ the attenuation occurs in the wall region. This worsen as we increase l_w^+, extinguishing the energetic inner peak for wires $l_w^+ > 100$. This peak value, u'^{2+}_{max}, is shown in figure 1(b) as a function of l_w^+ together with an experimental boundary layer [5] and a DNS channel data [2]. The region within the vertical dashed-lines correspond to the recommended length for wires in HWA to record turbulent statistics [5], $l_w^+ \approx$ 20-25. Figure 1(c) presents the attenuation factor $u'^{2+}_{fil}/u'^{2+}_{unf}$ as a function of y^+ and l_w^+, showing that it is in the buffer region where the maximum attenuation takes place for a given wire length. At $l_w^+ \approx 100$, an artificial outer peak emerges at $y^+ \approx 120$, and it moves to higher y^+ as l_w^+ increases. Figures 1(d-e) show one-dimensional pre-multiplied energy and missing energy spectra $k_{z,x}\phi_{uu}^+$ as functions of y^+, for l_w^+=25 and Re_θ=4500. For both spectra, 90% of the maximum missing spectrum is located at $y^+ \approx 15$, for wavelengths of $\lambda_z^+ \approx 70$ and $\lambda_x^+ \approx 800$ respectively. The effect of filtering in the spanwise direction is the attenuation of all the λ_x^+ wavelengths, and in the same way, filtering in x (time) attenuates all λ_z^+ wavelengths, although in that case the effect is weaker because the u structures are much longer than wide. Figure 1(f) shows the two-dimensional spectrum at $y^+ \approx 15$, highlighting the length-scale distribution of the energy and missing energy.

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